IMPACT OF CLIMATE CHANGE ON PHOTOCHEMICAL AIR POLLUTION IN SOUTHERN CALIFORNIA

A Paper From:
California Climate Change Center

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DRAFT PAPER

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

This study analyzed the effects of climate and emissions-related perturbations on ozone air quality in Southern California. The future year considered is 2050, with an assumed increase to double pre-industrial levels for global background levels of carbon dioxide. Effects of emission and climate-related forcing on air quality are superimposed on a summer 2005 high-ozone time period. Perturbations considered here include (a) effect of increased temperature on atmospheric reaction rates, (b) effect of increased temperature on biogenic emissions, (c) effect of increased water vapor concentrations, (d) effect of increased pollutant levels at the inflow (western) boundary, and (e) effect of population growth and technology change on emissions within the study domain. Various combinations of the above perturbations are also considered. The climate-related perturbations (a–c) led to combined ozone increases of up to 11 parts per billion for peak one-hour readings, with temperature and humidity effects dominating. The effect on ozone was greatly reduced when the temperature increase was made during nighttime hours rather than uniformly throughout the day. Increased pollutant levels at the inflow boundary also led to ozone increases up to 5 parts per billion. These climate and inflow-related changes offset some of the anticipated benefits of emission controls within the South Coast Air Basin.

Keywords: Ozone, climate change, biogenic emissions, temperature, humidity, Pacific Ocean inflow, 2050 emissions

1.0 Introduction

It has long been known that ozone air quality varies from day to day depending on meteorological conditions. A correlation between ozone levels and temperature is a well-known aspect of this relationship (Clark and Karl 1982; Sillman and Samson 1995; Lin et al. 2001; Aw and Kleeman 2003). Understanding of this relationship is needed both for short-term air quality forecasts, and in the longer term for assessing the possibility of a climate change penalty on air quality. This penalty is an increase in emission control requirements needed to offset changes in climate that increase the severity and/or frequency of air pollution episodes. Motivated by potential negative air quality and public health outcomes, researchers have been probing the effects of varying temperature on air quality for over a decade. Sillman and Samson (1995), for example, investigated the link between ozone concentrations and temperature using sensitivity analysis. Day et al. (2008) use summertime observations in a rural area of California to investigate the relationship between ozone and temperature changes. A number of research efforts have directly addressed the link between climate change and air quality by modeling future air quality under a number of future climate and emissions scenarios.

Model-based investigations of the effects of climate change on air quality have been conducted on both global and regional scales. Global analyses (Stevenson et al. 2005; Brasseur et al. 2006; Liao et al. 2006; Racherla and Adams 2006; Unger et al. 2006) simulate future meteorology and air quality under different climate scenarios. Racherla and Adams (2008) studied air quality in the eastern United States using a "unified" global model allowing them to incorporate air quality impacts from climate change that occur outside their U.S. study region. Jacobson (2008) uses simulations from a global model with a nested regional U.S. grid to examine health effects relating to climate-induced air quality changes. Tao et al. (2007) and Giorgi and Meleux (2007) use regional climate models to examine the effects of climate change on air quality over a smaller and more detailed scale.

High-resolution air quality models are needed to study local effects on air quality, such as complex terrain, spatially distributed emissions, and fine-scale differences in expected population changes. Studies such as Aw and Kleeman (2003), Steiner et al. (2006), and Kleeman (2008) refine the scale of interest to focus on air quality in urban areas in California. These studies incorporate predictions of future temperature changes and various feedbacks that may result, but do not account for changes in other important meteorological variables such as atmospheric circulation patterns or precipitation.

Other studies have examined the effects on air quality of changing the frequency of stagnation events. Mickley et al. (2004) report that predicted changes in cyclonic activity leads to a lengthening of stagnation events across the eastern and mid-western United States, creating longer and worse air pollution episodes. Leung and Gustafson (2005) find evidence of increasing stagnation in Southern California during the fall, causing similar air quality effects.

To date most modeling studies have ignored air quality implications of temperature change due to changing land use. Duffy et al. (2006) discuss increases in observed surface temperatures for California over the last 50 years, pointing out that temperature increases have been higher during the nighttime than daytime. They argue that global climate models do not represent accurately the seasonal or diurnal changes in the observed temperature record in California since 1950. Duffy et al. (2006) show that unmodeled forcings due to changes in land-use and

irrigation affect trends in daily maximum temperatures. Bonfils and Lobell (2007) and Lobell and Bonfils (2008) show that increases in irrigation have had a cooling effect on daytime temperatures during summer.

The objective of this study is to predict potential effects of future changes in climate, population, and emissions on ozone air quality in Southern California. Outcomes at different locations throughout the Los Angeles area help to quantify a climate change penalty that may offset some of the benefits of emission control policies.

2.0 Methods

The effects on ozone air quality of changes in five different factors (temperature, humidity, biogenic emissions, inflow boundary conditions, and anthropogenic emissions) are evaluated in Southern California. Each of these factors is examined individually. In addition, the combined effects of changes in temperature, biogenic emissions, and humidity represent an aggregate climate-related effect on air quality. The combined effects of future anthropogenic emissions and changes in inflow boundary conditions represent effects of population growth and technology change, both locally in Southern California and globally. Each of these scenarios is compared to a base-case high-ozone episode from summer 2005.

Air quality is modeled in Southern California for the base case period of July 14–19, 2005, when observed ozone concentrations peaked at over 100 parts per billion (ppb) at many inland locations. This air pollution episode is one of several that have been used to support control strategy design in the 2007 Air Quality Management Plan for the South Coast Air Basin (i.e., the Los Angeles area). The model domain (110×74 grid cells with 5 kilometer [km] horizontal resolution) is centered over downtown Los Angeles, extending west over the Pacific Ocean past the Channel Islands, and east over the Mojave Desert. The domain extends from northern Mexico to the south end of San Joaquin Valley, as shown in Figure 1. The vertical dimension is divided into 25 layers extending to ~15 km above sea level, with a telescoping grid starting at a 36 meter (m) layer thickness near ground level and increasing to 6.5 km near the tropopause.

The Community Multiscale Air Quality model (CMAQ) version 4.6 (Byun and Schere 2006) is used to predict base case and future air quality. The SAPRC99 chemical mechanism (Carter 2000) is applied with boundary conditions similar to Steiner et al. (2006). The nitric oxide (NO) and nitrogen dioxide (NO_2) inflow (western) boundary conditions were reduced from 1 ppb each to 0.01 and 0.03 ppb, respectively, based on Nowak et al. (2004). Meteorological fields were developed by the South Coast Air Quality Management District (SCAQMD 2007) using the National Center for Atmospheric Research (NCAR) Mesoscale Meteorological model (MM5) version 3.6.1. Three two-way nested domains were used with spatial resolution of 45 km, 15 km, and 5 km. Only the 5 km grid MM5 results were used in the present study to drive air quality model calculations.

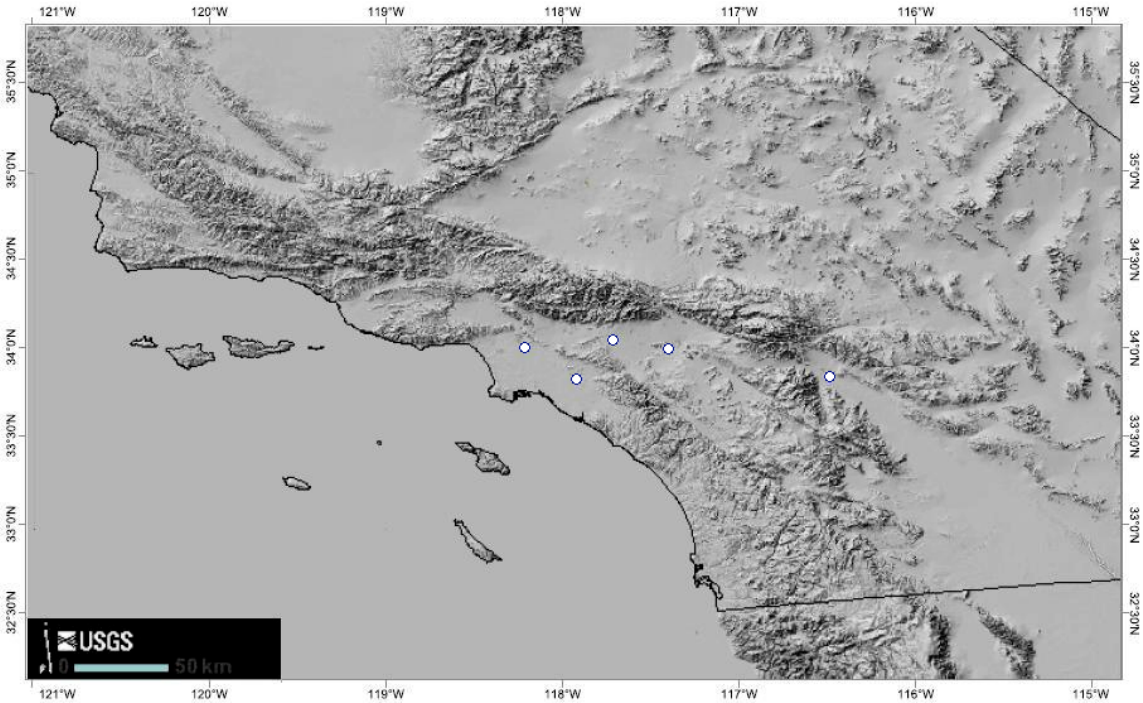


Figure 1. Map of Southern California study domain used for air quality modeling in the present study. Locations highlighted from left to right: Los Angeles, Anaheim, Pomona, Riverside, and Palm Springs.

The base case emission inventory was provided by the California Air Resources Board (Jackson, pers. comm. 2007). Separate hourly and day-specific gridded estimates of mobile, point, and area source emissions were developed and combined with day-specific biogenic emission estimates developed using the BEIGIS model (Scott and Benjamin 2003).

Perturbations to the base case air quality model are developed and applied using results from a global and regional climate modeling study by Snyder et al. (2002). A doubling of preindustrial global background carbon dioxide (CO_2) levels from 280 to 560 parts per million (ppm) is the basis for future climate calculations. Although Snyder et al. (2002) increased only CO_2 in their global and regional climate modeling study, similar climate changes would be expected for a smaller CO_2 increase if other greenhouse gases were increased to yield an overall 2× CO_2 equivalent scenario. The domain used in the regional climate model was centered on California with a relatively high (for climate models) horizontal resolution of 40 km. This resolution is needed to capture the wide variety of elevations, land cover types, and microclimates that are found within California. The regional climate model was forced using results of the NCAR parallel climate model for the 2× CO_2 scenario. See Snyder et al. (2002) for further details. Predicted temperature changes for July range from 1.6°C to 3.5°C (2.9°F to 6.3°F), with the larger changes predicted to occur further inland.

Perturbations to the base case air quality model were considered separately to isolate the effects of individual variables. Temperature changes affect chemical reaction rates in the model, but these changes were not linked to other variables such as wind speed or planetary boundary

layer height, which remained the same as in the base case. The effect of increased temperatures on biogenic emissions of volatile organic compounds (VOC) was modeled as a separate effect.

Biogenic emissions of isoprene and methyl-butenol are sensitive to temperature and light, whereas terpenes are sensitive to temperature but not light. For the future temperature scenario, emissions of isoprene and terpenes were scaled using algorithms described by Guenther et al. (1993). Methyl-butenol emissions were adjusted following Harley et al. (1998).

Assuming relative humidity remains constant in the future climate scenario, absolute humidity is adjusted given the new (higher) temperatures. This calculation adjusts the ratio of grams of water/kilograms of air to maintain the same relative humidity under future temperature conditions. Note that in the "humidity only" scenario, relative and absolute humidity both increase, while temperature is held constant. For the combined climate case, relative humidity is unchanged between future and base case scenarios, as both absolute humidity and temperature increase.

Future anthropogenic emissions in 2050 were estimated from current emissions, scaled to account for population growth and technology change. Population growth was estimated at the county level by the California Department of Finance (2007). Technology improvements and increased regulation of sources are estimated to reduce VOC, carbon monoxide (CO), and nitrogen oxide (NO_x) emission factors by 80% below present-day (circa 2000, already controlled) levels. Following Steiner et al. (2006), growth in the diesel sector is specified to be twice that of other sectors and thus NO_x emissions are predicted to increase in some areas (due to rapid growth), whereas VOC and CO emissions generally decrease. This future emission scenario represents business as usual, and does not reflect effects of recent increases in fuel prices, or the effects of efforts to reduce greenhouse gas emissions to 80% below 1990 levels by 2050.

Future inflow boundary conditions were adjusted following Steiner et al. (2006), using concentrations of CO, ozone, and methane predicted by the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 2001) for the A1B scenario in 2000 and 2050. To highlight the potential effects from increasing emissions in Asia, ozone concentrations were increased by roughly double the amount predicted in the A1B scenario. On the western boundary, CO concentration was increased by ~30%, methane concentration was increased by ~40%, and ozone was increased by ~30%. No adjustments were made to inflow NO_x, as concentrations across much of the domain were several orders of magnitude higher than the inflow concentrations used here.

3.0 Results and Discussion

Base case ozone predictions were compared to observations at 83 surface sites. Comparing all ozone observations above 40 ppb with model predictions, a normalized bias of +3% and a normalized error of 30% were found. The spatial distribution of ozone in the model matches that seen in the observations, with the best agreement found in the urbanized areas around Los Angeles. Figure 2 shows a comparison of model output to observations at five locations. The modeling domain is well-suited to studying photochemical air pollution in the South Coast Air Basin. In contrast, both San Diego and the southern San Joaquin Valley lie at the extreme edges

of the Southern California study area used here, and as such are subject to larger uncertainties due to their proximity to northern and southern boundaries of the modeling domain.

Further assessment of air quality model performance for the base case was done by evaluating model predictions against hourly observations of ozone precursors such as carbon monoxide (CO) and total oxidized nitrogen (NO_y). Normalized biases were –26% for CO and –3% for NO_y. Corresponding normalized gross error statistics were 45% for CO and 59% for NO_y. A source of uncertainty in these comparisons is that NO_y observations lie somewhere between NO_x (i.e., $NO+NO_2$ only) and true NO_y: the NO_x analyzers in the routine air monitoring network in general are not equipped with externally mounted converters so there may be significant inlet losses of some NO_y species such as nitric acid. Available observations for nonmethane hydrocarbons (NMHC) were so sparse that no meaningful model evaluation for that pollutant was possible.

A series of model runs was conducted to determine the sensitivity of air quality in Southern California to future changes in emissions and climate. Figures 3 through 7 show differences in input data and resulting changes in ozone air quality between various future scenarios and the summer 2005 base case. The spatial patterns of ozone changes are shown at 3 p.m., which is a high-ozone time of day. Time series plots showing ozone changes at specific locations are presented and discussed later.

The effect of increased temperatures on chemical reaction rates is to increase peak ozone levels across the study domain. The largest difference is found at Riverside. Figure 3 shows the change in temperature and corresponding peak ozone response. Inland areas that will experience larger future temperature increases and are close enough to Los Angeles to be strongly influenced by its emissions experience the strongest effects of temperature change.

Figures 4 and 5 show changes in biogenic emissions and humidity and the corresponding peak ozone responses. The same spatial patterns of effect as in Figure 3 can be seen for both humidity changes and biogenic emission changes that are a function of temperature. Little change in ozone is seen at coastal areas of Orange and Los Angeles Counties, but a stronger ozone response is seen inland. The effects of biogenic emission changes are further complicated by the spatial distribution of these emissions, present mostly in the surrounding mountains rather than within urbanized areas. Over much of the domain, biogenic emissions increased by 20%–35% compared to the base case as a result of higher temperatures.

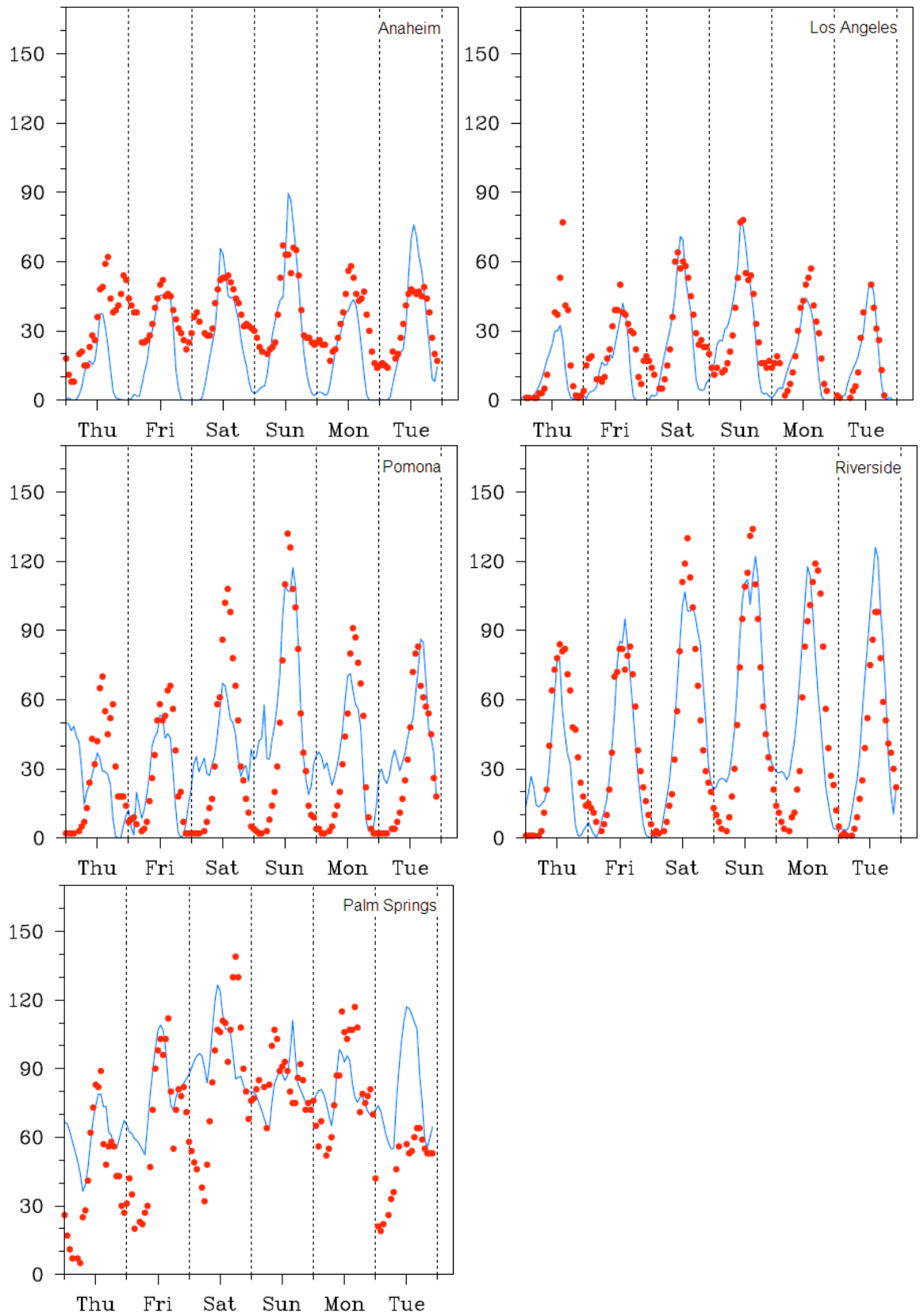


Figure 2. Comparison of base case model output (blue) to ozone measurements (red) at five sites

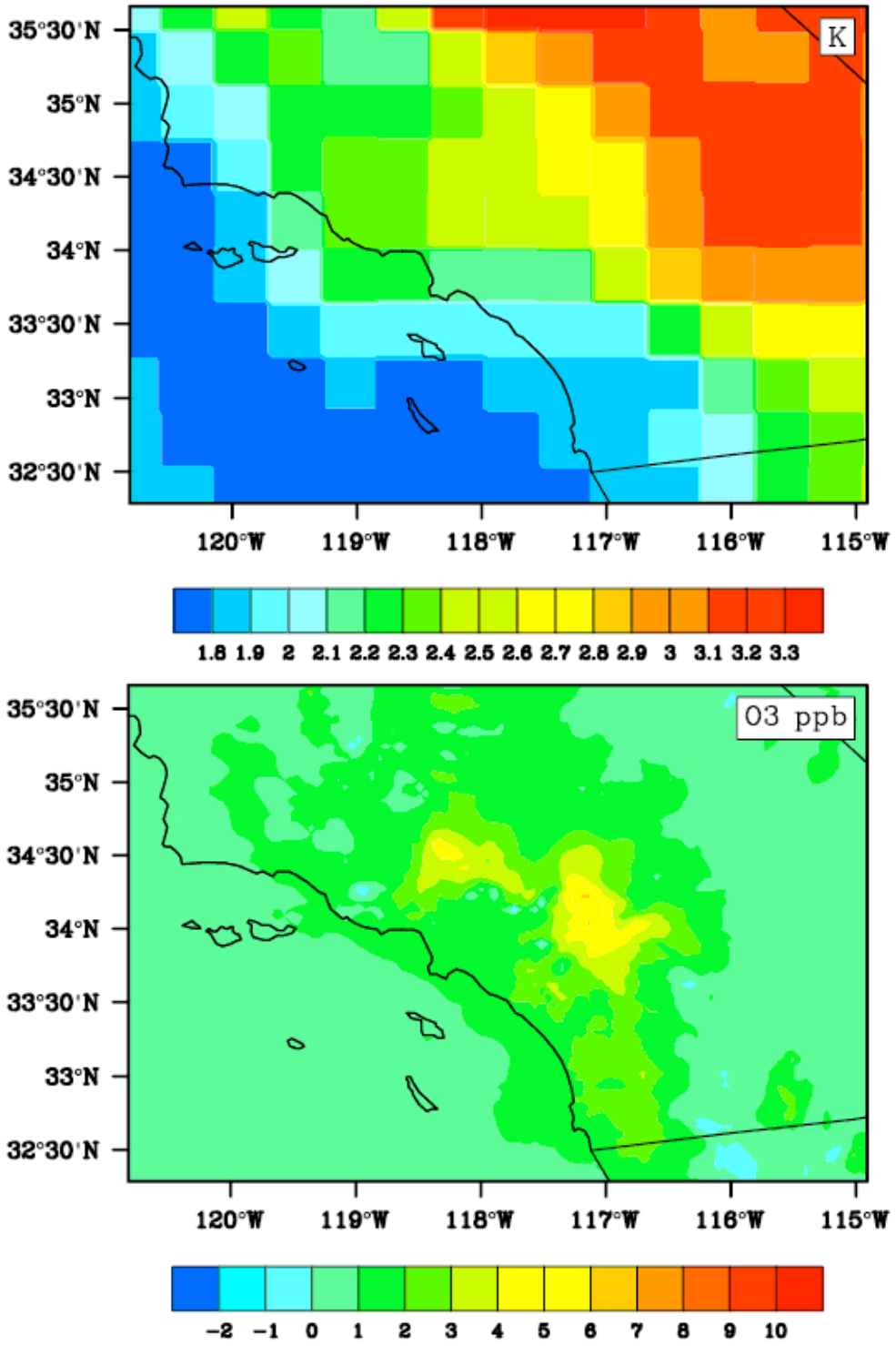


Figure 3. Difference between future and base case temperature and ozone concentrations on weekdays at 1500

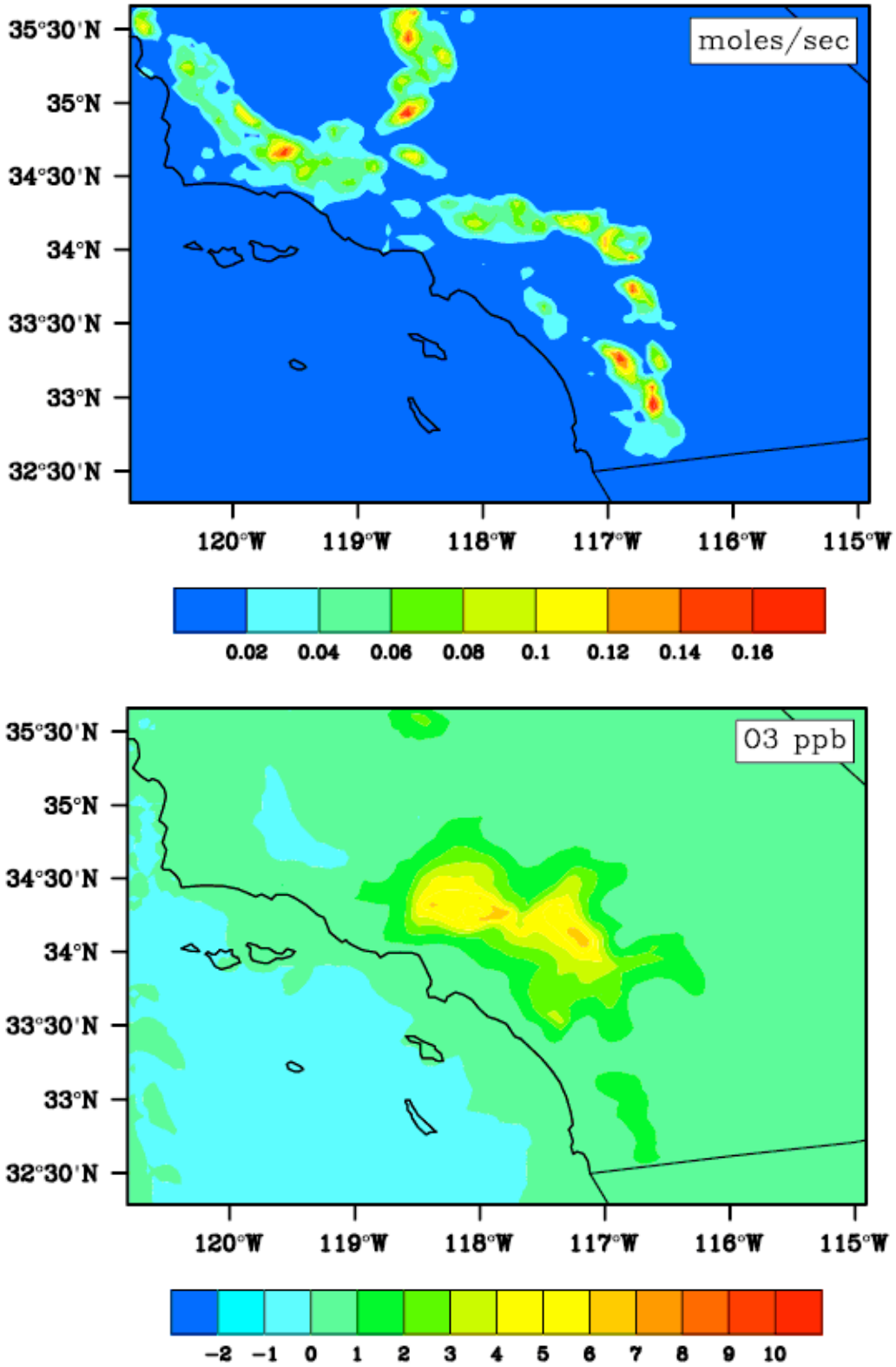


Figure 4. Difference between future and base case biogenic emissions and ozone concentrations on weekdays at 1500

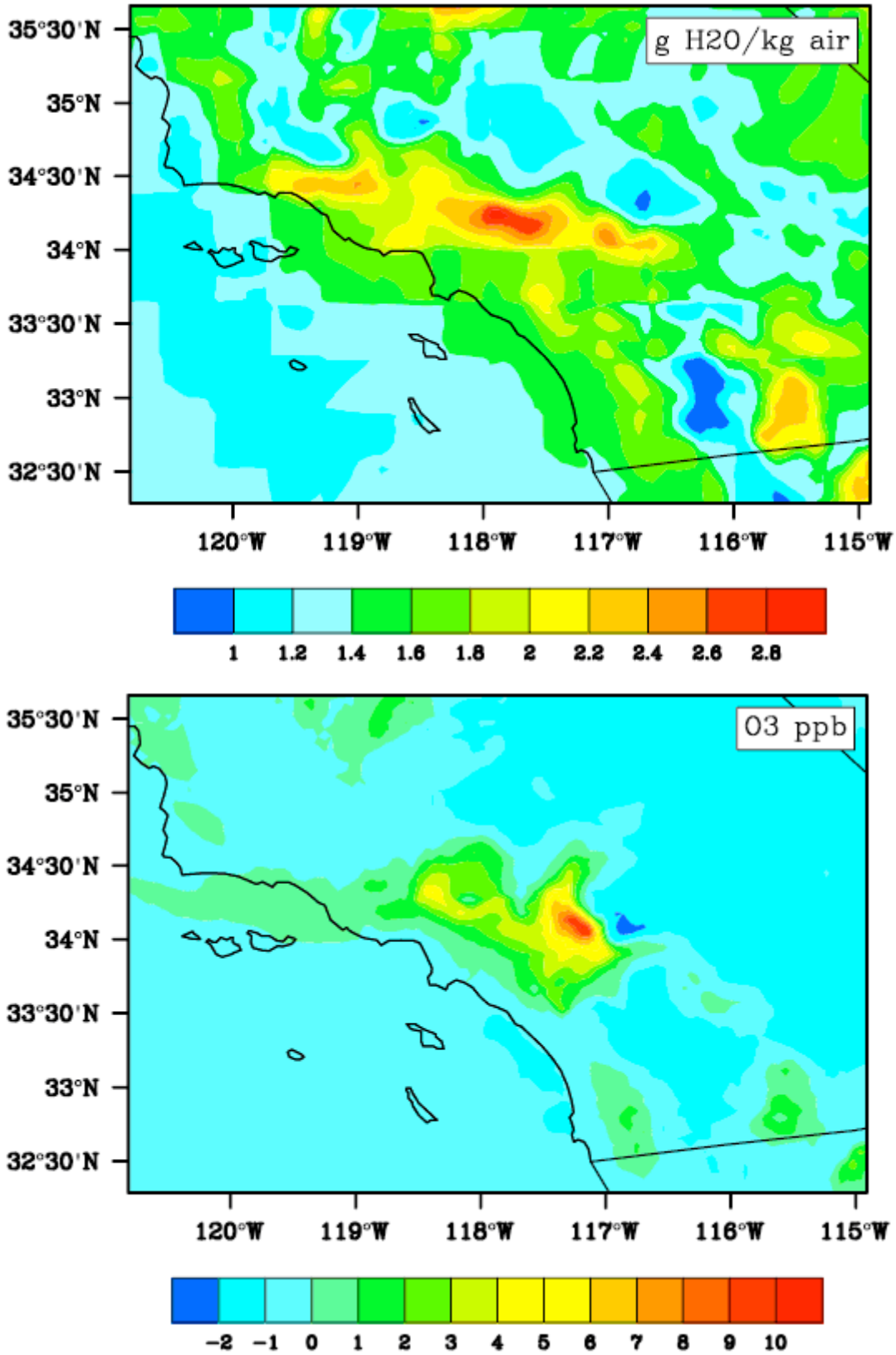


Figure 5. Difference between future and base case absolute humidity and ozone concentrations on weekdays at 1500

Figure 6 shows changes in NO and ozone concentrations between future anthropogenic emission and base case scenarios. Under the future emission scenario, emissions of NO_x, VOC, and CO generally decrease across the domain. Coastal areas see reductions of 35%–50% in NO_x emissions and even larger reductions in VOC. The resulting effects on ozone were mixed, due to spatial differences in ozone sensitivity to VOC versus NO_x emissions. Central Los Angeles shows an increase in peak ozone levels of up to 5 ppb, whereas Riverside sees a larger decrease (~12 ppb).

Increased pollutant concentrations at the western inflow boundary increase peak ozone levels consistently across all the sites except Palm Springs (see Figure 7). The separation of Palm Springs by the San Gorgonio Mountains from the western inflow boundary is clear, although it is interesting to note that ozone in Palm Springs reacts similarly to Riverside to changes in anthropogenic emissions.

Figure 8 shows the ozone air quality outcomes of various combinations of the above five scenarios, relative to the base case. A combined climate forcing case (Figure 8a) incorporates the changes to temperatures, absolute humidity, and biogenic emissions. Increases in peak ozone are seen across the domain, ranging from 3–15 ppb, with the highest increases occurring inland near Riverside. The future emissions/BC scenario (Figure 8b) includes changes to anthropogenic emissions and western (inflow) boundary conditions and shows increases in peak ozone near the coast and decreases in peak ozone at locations further inland. Finally, a combined scenario including both climate-related and emissions/BC changes all together at once shows increases in peak ozone at most locations, with decreases seen only far inland (Figure 8c).

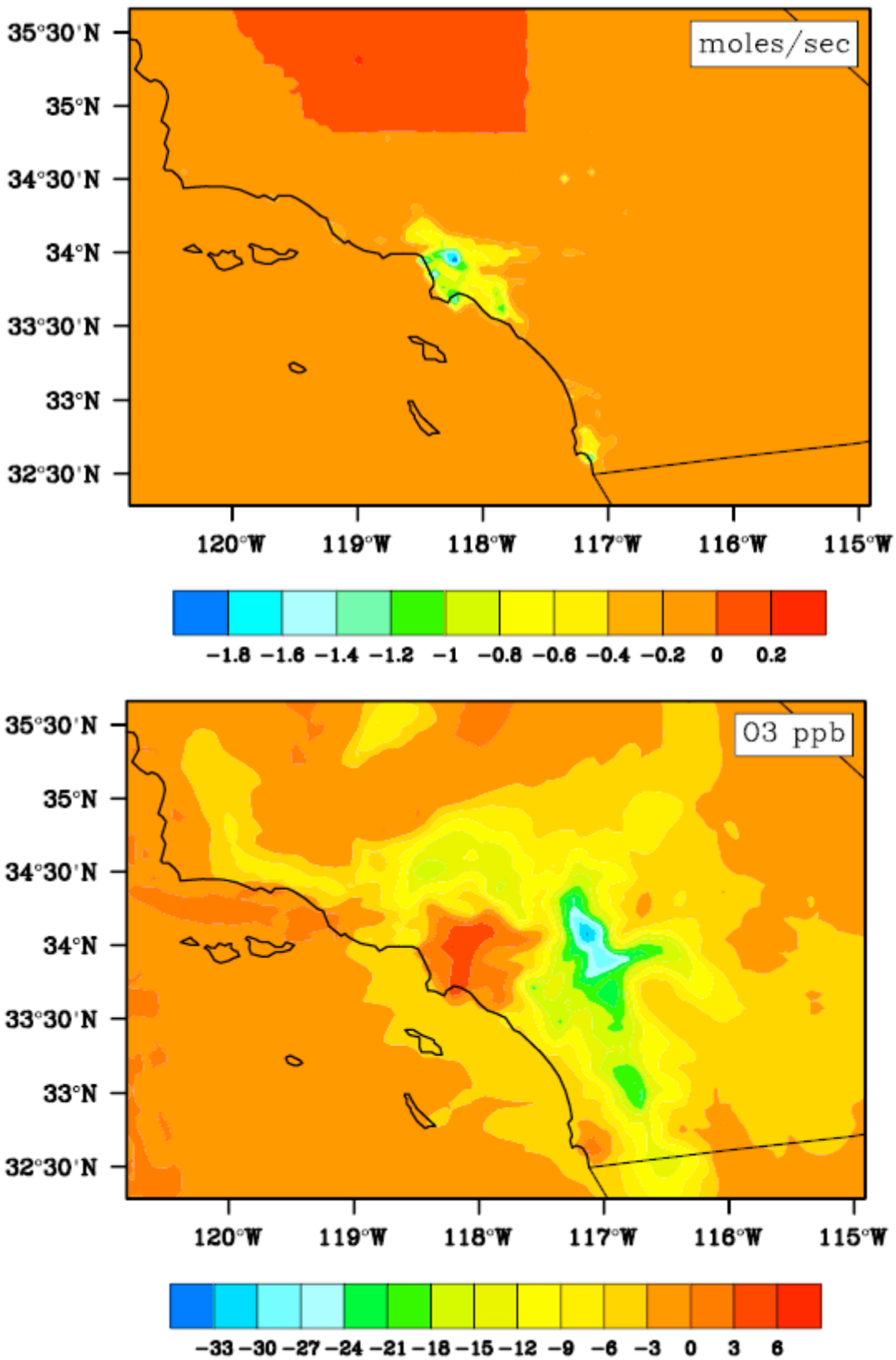


Figure 6. Difference between future and base case NO and ozone concentrations on weekdays at 1500. (Future anthropogenic emissions scenario.)

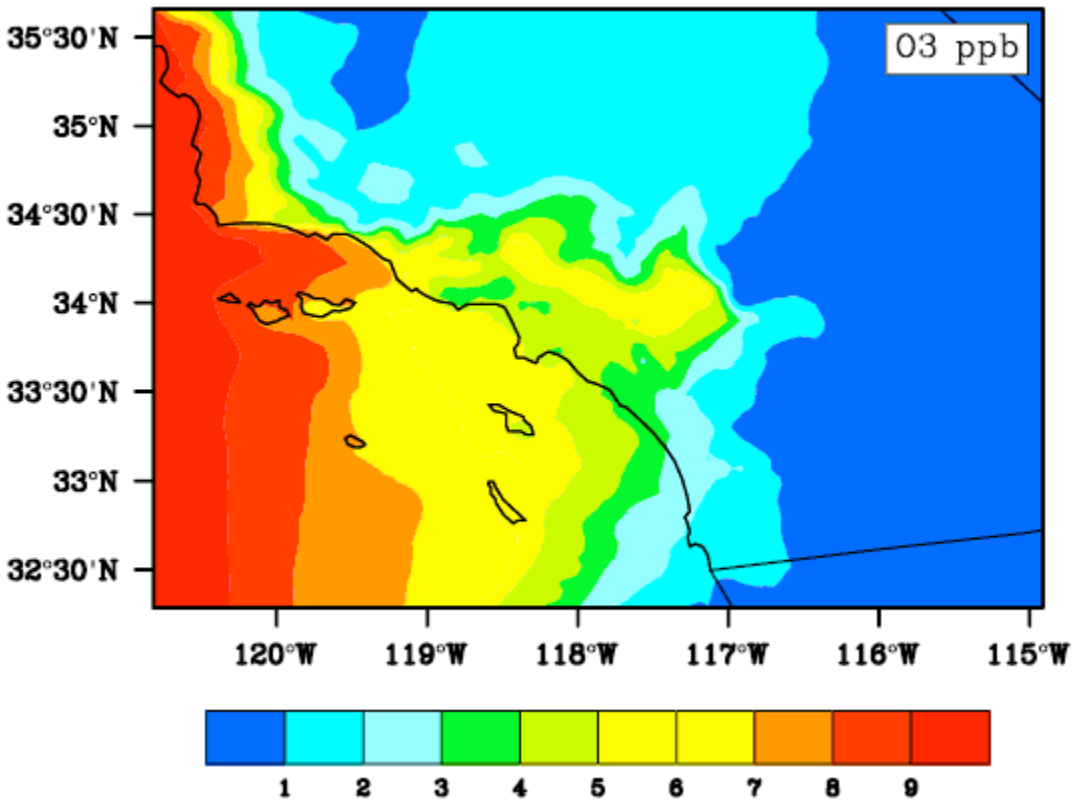
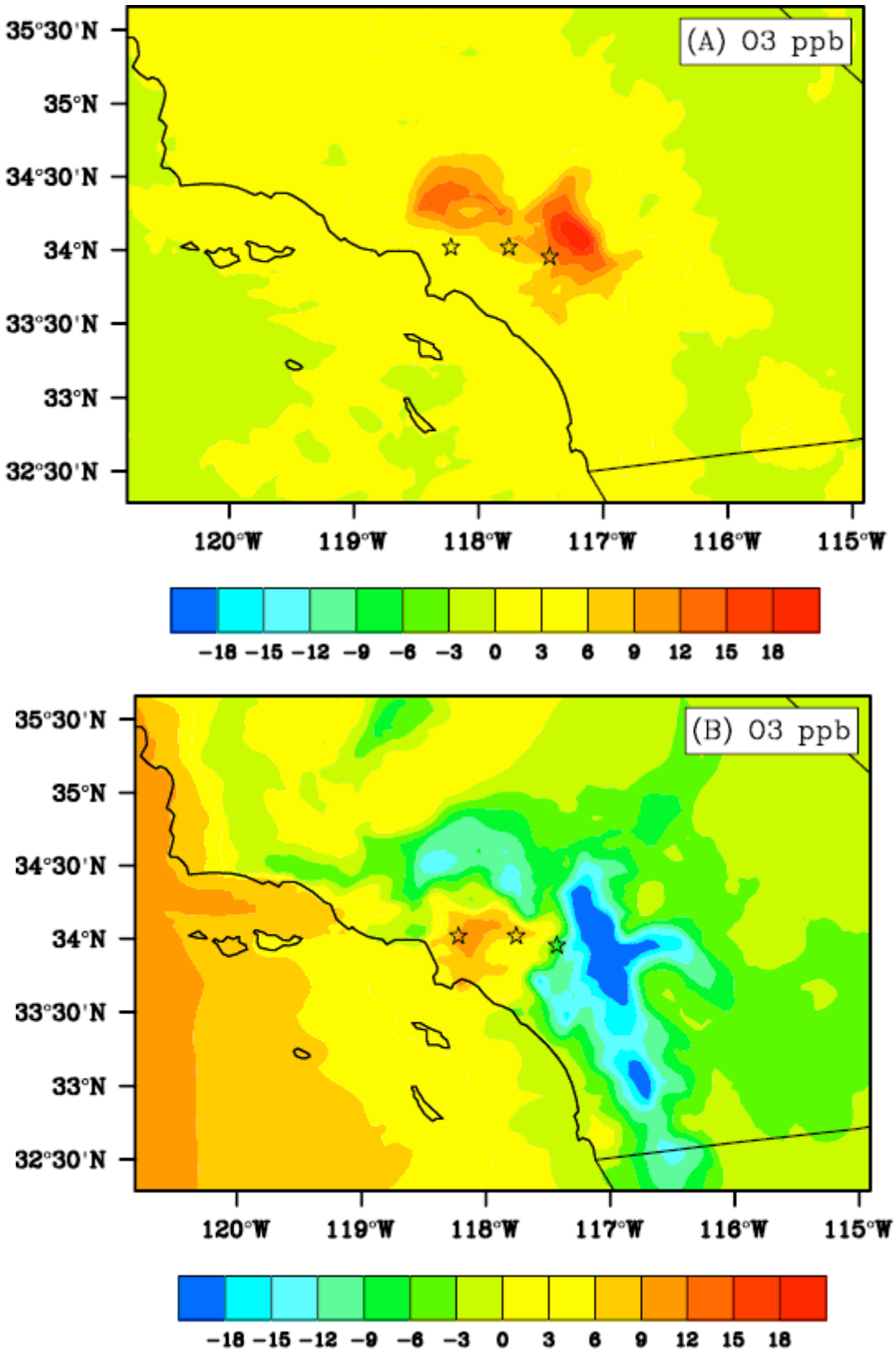


Figure 7. Difference between future and base case O_3 concentrations on weekdays at 1500. (Future inflow scenario.)


(A) O3 ppb
35°30'N
35°N
34°30'N
34°N
33°30'N
33°N
32°30'N
120°W
119°W
118°W
117°W
116°W
115°W
−18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18
(B) O3 ppb
35°30'N
35°N
34°30'N
34°N
33°30'N
33°N
32°30'N
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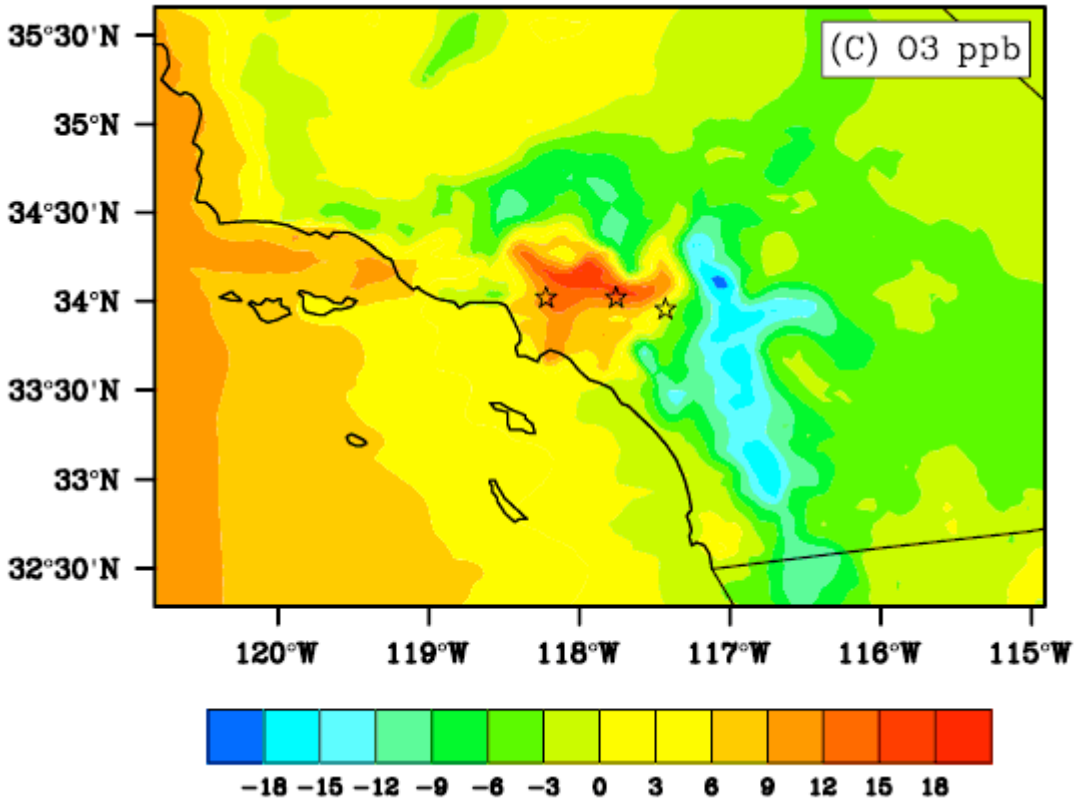


Figure 8. Difference between future and base case O_3 concentrations on weekdays at 1500. The three stars show the locations of (from left to right) downtown L.A., Pomona/Claremont, and Riverside. Scenarios: (a) Future climate perturbations (temperature, absolute humidity, biogenic emissions), (b) Future anthropogenic perturbations (anthropogenic emissions, inflow concentrations), and (c) all perturbations.

Table 1 summarizes changes in ozone between each future scenario and the base case. Combined scenarios (rows 6–8 in Table 1) are not linear combinations of earlier scenarios, but represent results of additional model runs incorporating various combinations of the individual perturbations, as noted in Table 1.

The locations shown in Table 1 were chosen to span future air quality outcomes in populated areas near Los Angeles. Anaheim is located in Orange County, south of Los Angeles. The Central Los Angeles site is located near downtown, approximately 20 km from the coast. Pomona, Riverside, and Palm Springs are located progressively further east of Los Angeles. Pomona is ~40 km east of Los Angeles and Riverside is ~40 km east of Pomona. Although the terrain becomes more complex traveling east from Los Angeles to Riverside, no major mountains are located between the cities. East of Riverside the San Gorgonio Mountains rise with peaks over 3 km above sea level, separating Palm Springs and the Mojave Desert from the greater Los Angeles area (Figure 1 shows a map of the domain).

Table 1. Average weekday difference in ozone (ppb) at 3 p.m. local time between the specified run and the base case scenario

	Anaheim	Central L.A.	Pomona	Riverside	Palm Springs
1) Temperature	1.3	1.6	1.5	3.3	2.2
2) Biogenic VOC	0.6	1.0	2.8	2.9	0.9
3) Humidity	0.1	0.9	3.4	4.4	-1.1
4) 2050 Emissions	1.4	4.3	2.5	-13.5	-7.9
5) Inflow BC	4.3	4.3	5.5	5.4	1.0
6) Combined 1-3	2.2	3.5	8.5	11.3	2.1
7) Combined 4-5	6.1	8.8	8.3	-8.2	-6.9
8) Combined 1-5	7.9	11.2	16.0	-0.3	-5.6

Overall there are large changes in peak ozone due to both future climate and future emissions. Scenario 8 (Figure 8c) combines all of the input perturbations mentioned above. Ozone increases across the greater Los Angeles area and decreases east of Riverside. The changes in peak ozone range over ±17.5 ppb. Further consideration of future emission scenarios and control policies is recommended. More detailed forecasts of future (2050) emissions are needed. Also air quality management plans may need to be adjusted to account for ozone increases due to climate change (i.e., the so-called climate penalty).

3.1. Temporal Patterns of Ozone Change

Riverside lies near the interface between positive and negative ozone outcomes under the combined scenario of future climate, emissions, and inflow boundary conditions. Figure 9 shows a predicted difference between base case and future scenario ozone concentrations by time of day at five locations. The magnitude and even the direction (i.e., increase vs. decrease) of the change in ozone concentrations at Riverside are time dependent. The ozone response differs both by time of day, and for weekdays versus the weekend.

Future ozone is closest to base case predictions around noon, although the sign of the change varies from day to day at Riverside. At other sites, such as Pomona and downtown Los Angeles, future ozone concentrations are consistently higher than in the base case. This is due to a combination of air quality penalties attributable to climate change and higher inflow boundary conditions and a local undesired effect of lower NO_x emissions on ozone in upwind areas, where the system is NO_x-saturated.

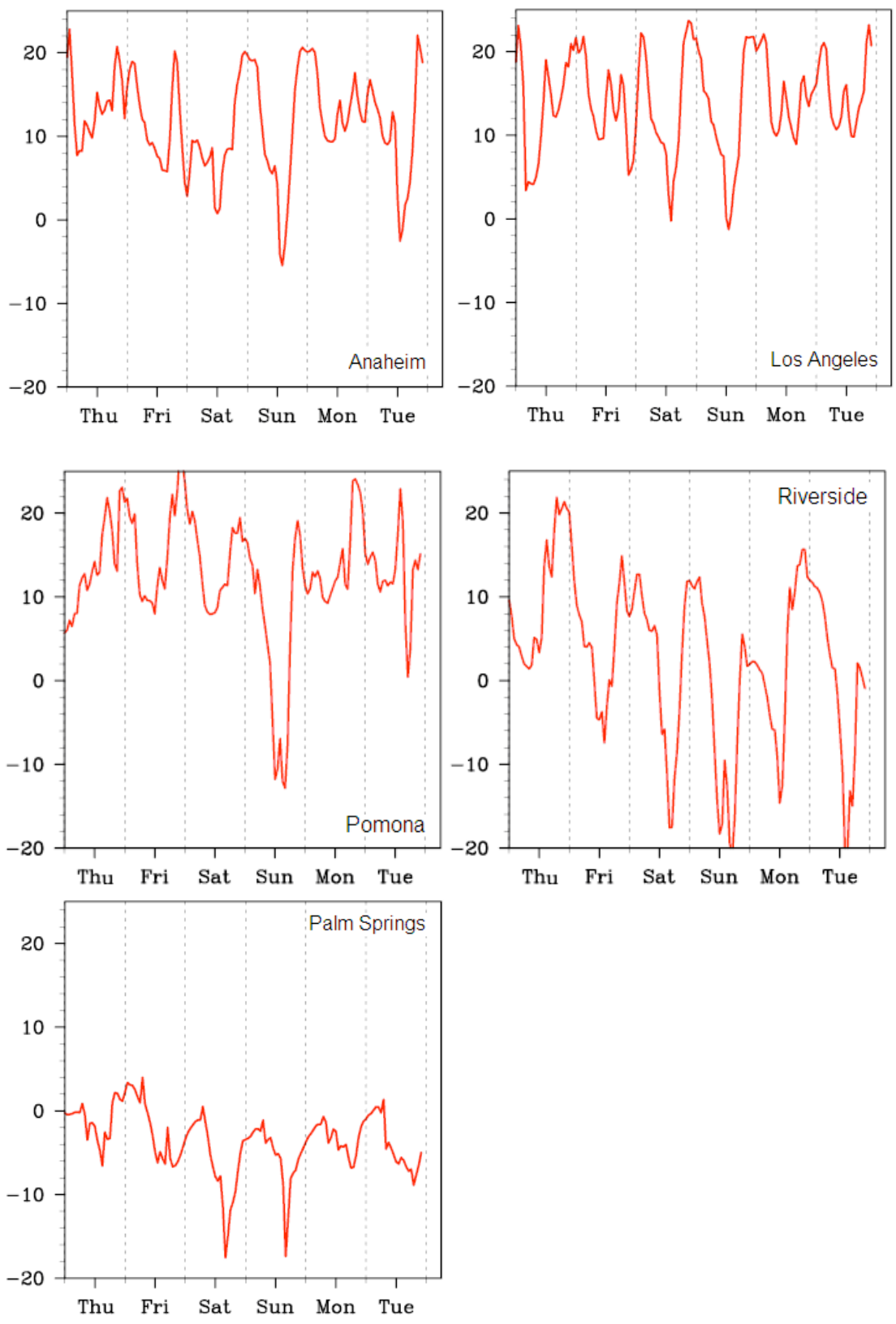


Figure 9. Difference between base case and future ozone concentrations (ppb) by time at five locations. (All perturbations scenario.)

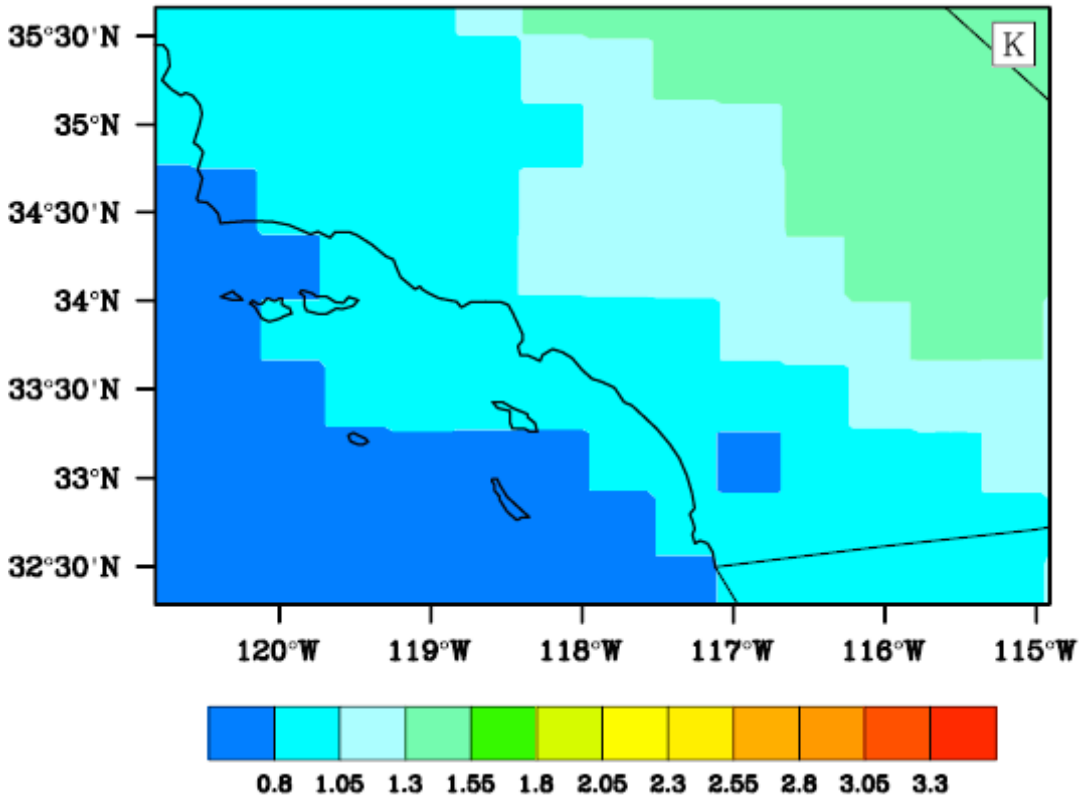
3.2. Future Temperature Change

Temperature increases provided by Snyder et al. (2002) did not include information on possible time-of-day dependence of temperature changes. Historically (i.e., from 1950 to present day), observed temperature increases during summer months have been largest at nighttime hours in many areas of California, and little increase in daytime maximum temperatures has been reported in the observed record of surface temperatures (Bonfils et al. 2008). To evaluate the effect of a diurnally varying (rather than uniform) temperature increase on atmospheric chemistry and biogenic VOC emissions, an alternate form of the temperature perturbation was developed. Future temperatures were recalculated as a function of time of day:

$$T(t) = T_0(t) + \Delta T\left[1 + 0.8\cos\left(\frac{2\pi t}{24}\right)\right]$$

Where T_0 is the original temperature in the base case scenario, t is time in hours past midnight, and ΔT is the 24-hour average increase in temperature predicted by Snyder et al. (2002) for the month of the July, which is appropriate for the base case episode being considered here. The amplitude of the oscillatory component (0.8) is arbitrary, but was chosen so that most but not all of the temperature increase occurs at night. This creates a future temperature profile consistent with a past record of summer daytime cooling due to increased irrigation of 0.14°C to 0.25°C (0.25°F to 0.45°F) per decade in California (Bonfils and Lobell 2007).

Much of the increase in peak ozone predicted with a uniform temperature increase disappears when the temperature increase occurs mostly at night. Figure 10 shows changes in predicted ozone relative to the base case at 3 a.m. and 3 p.m. on weekdays. More generally, ozone concentrations show little change at any time of day relative to the base case when temperature increases are applied mostly at nighttime hours (see Figure 11).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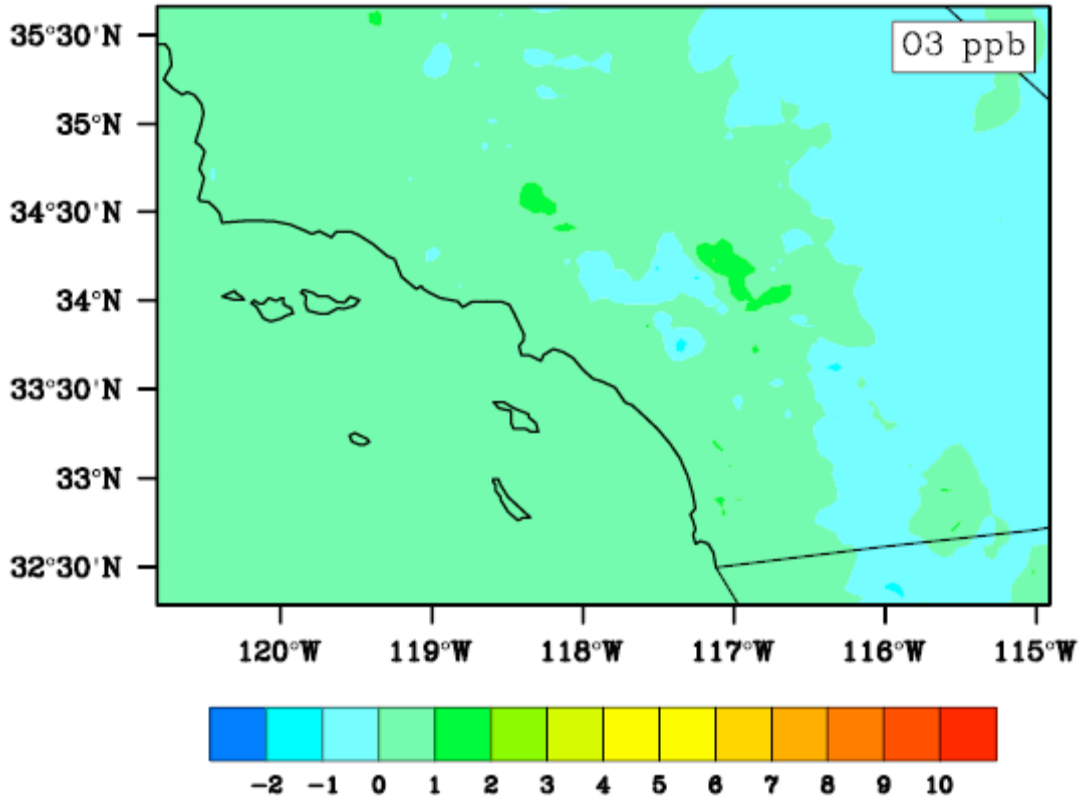
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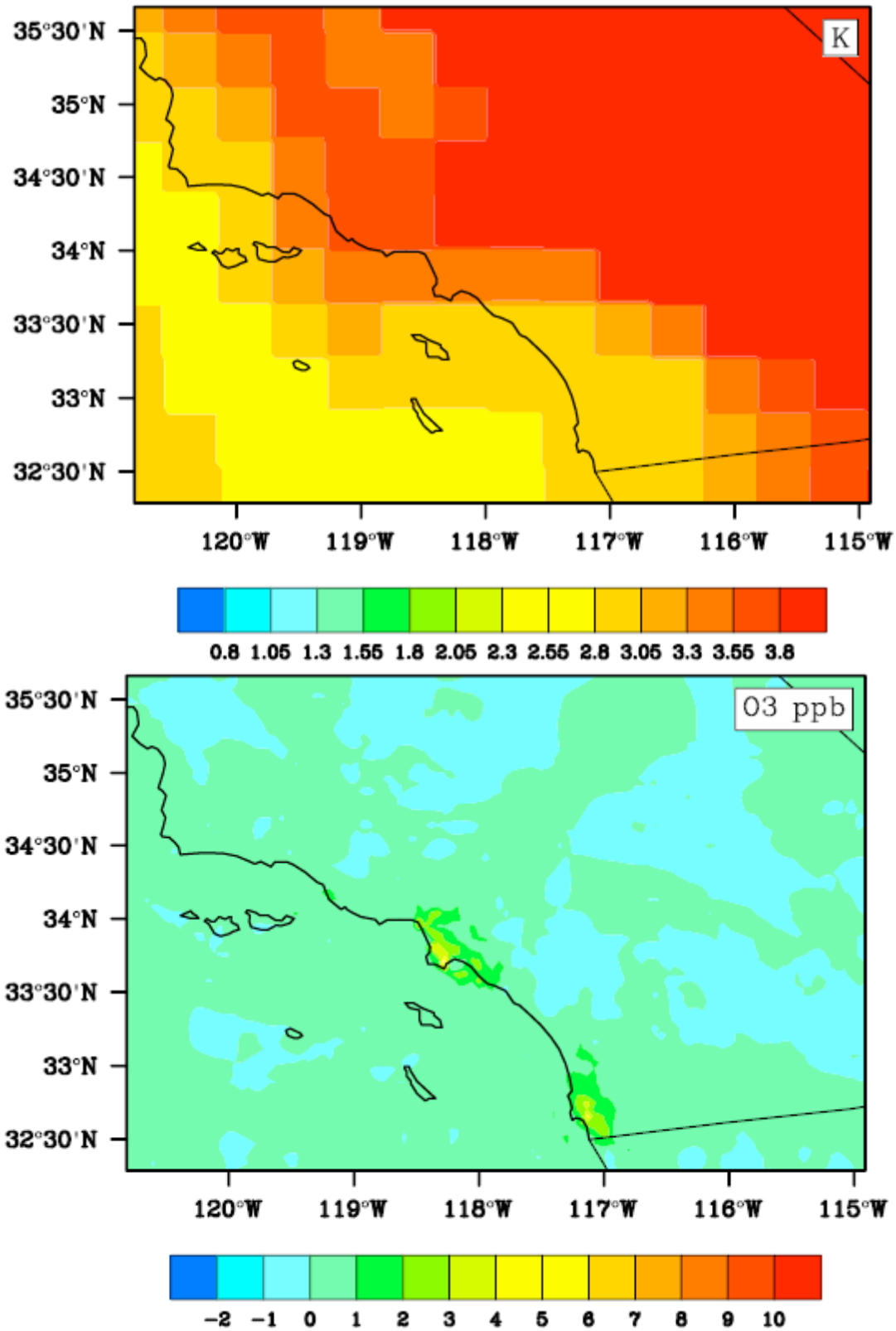


Figure 10. Difference between future and base case temperature and ozone concentrations on weekdays at 300 (second two panels) and 1500 (first two panels). Temperature changes in the scenario are adjusted by time of day.

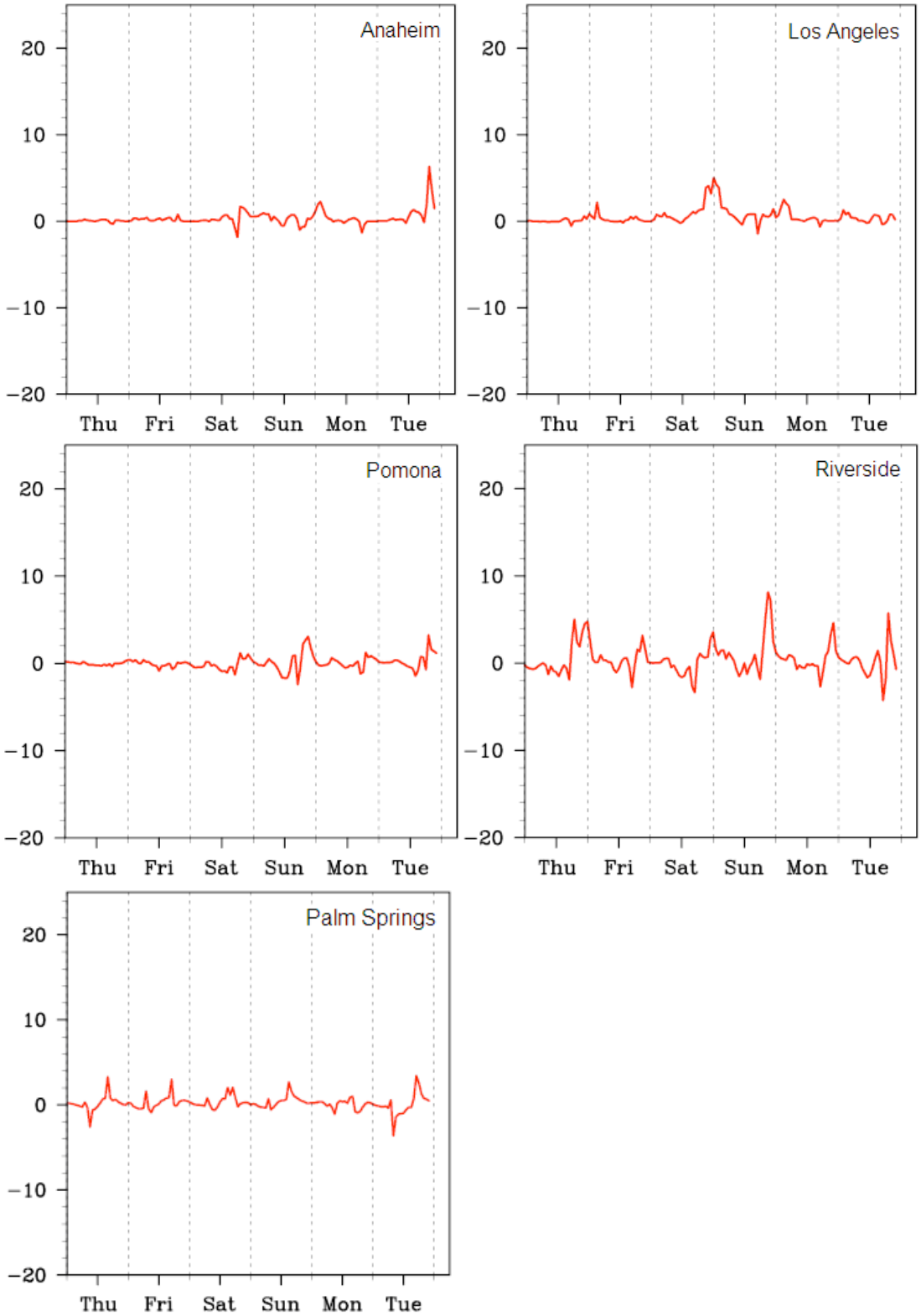


Figure 11. Difference between base case and future ozone concentrations (ppb) by time at five locations. (Future temperature scenario with future temperature change adjusted by time of day.)

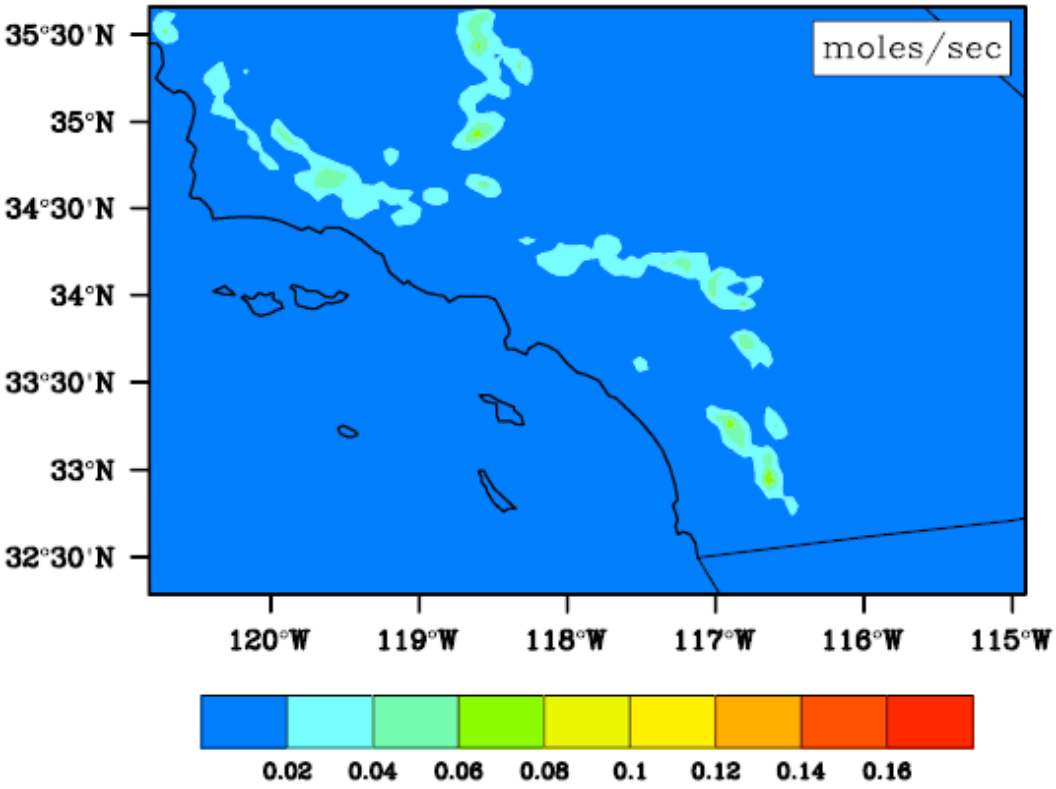
Similar results were found when biogenic emissions were recalculated using diurnally varying temperature changes. Emissions of both isoprene and methyl-butenol are temperature and light-sensitive, and therefore emissions of these compounds are zero at night. Nighttime temperature increases do increase terpene emissions, but the absolute effect of temperature increases on terpene emissions at night is reduced because baseline temperatures are lower at night. Figure 12 shows changes in 3 a.m. and 3 p.m. ozone due to revised estimates of biogenic VOC emission increases. Again, ozone concentrations do not increase nearly as much as seen previously when the effect of higher temperatures was applied uniformly throughout the day. Comparing Figure 12 to Figure 4, one should note peak ozone increases of 5 ppb with uniform warming, and only minor increases with the diurnally varying temperature perturbation.

This analysis emphasizes the importance of the diurnal pattern of future temperature changes to the assessment of climate change impacts on ozone air quality. Nighttime temperature increases have less effect on ozone production than similar temperature increases that occur at midday. However, the historical record of temperature increases is not necessarily a good predictor of future warming. Irrigation, which increased over the last century in California, is unlikely to increase in the same manner in future years. Loss of agricultural lands to urbanization and scarcity of water may slow or reverse the expansion in irrigated lands. In fact the amount of irrigated land in California has remained relatively stable since the 1980s (Bonfils and Lobell 2007). Thus, the mitigating effect of increased irrigation on daytime warming is unlikely to be repeated over the next 50 years.

4.0 Summary and Recommendations

This study investigated the effects of future climate change, inflow pollutant boundary conditions, and anthropogenic emissions on ozone air quality in Southern California. Future temperature changes were predicted at high spatial resolution in California for a scenario of 2× pre-industrial CO_2 levels by Snyder et al. (2002). Future emissions were predicted starting from the baseline emission inventory, factoring in expected population growth and likely advances in emission control technologies.

Globally driven climate changes led to ozone increases throughout the study domain. In this study, climate change affected ozone levels through three mechanisms: increased temperature, increased humidity, and increased biogenic VOC emissions. These effects correspond to a climate penalty on air quality: additional controls on anthropogenic emissions will be needed to offset the undesired effects on ozone. Likewise, future increases in pollutants entering Southern California via inflow from the Pacific Ocean will increase ozone levels, with coastal areas being especially vulnerable to this effect. The response of ozone air quality to future emission changes varied by location, with ozone increases predicted in upwind areas and decreases further downwind.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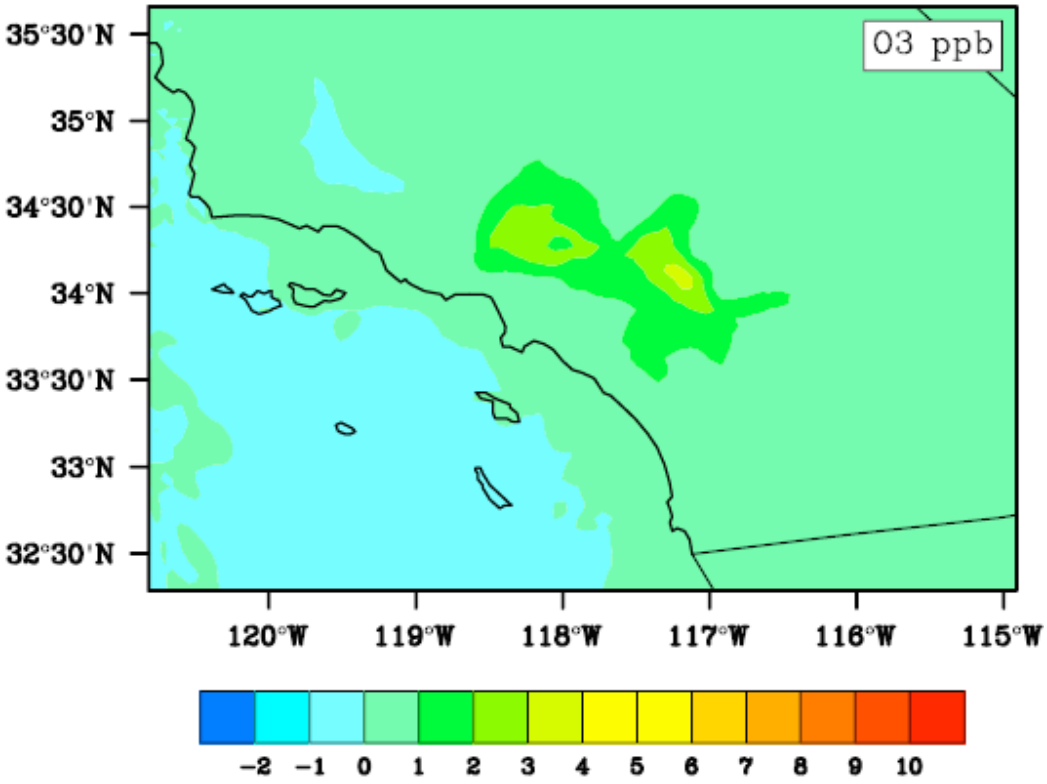
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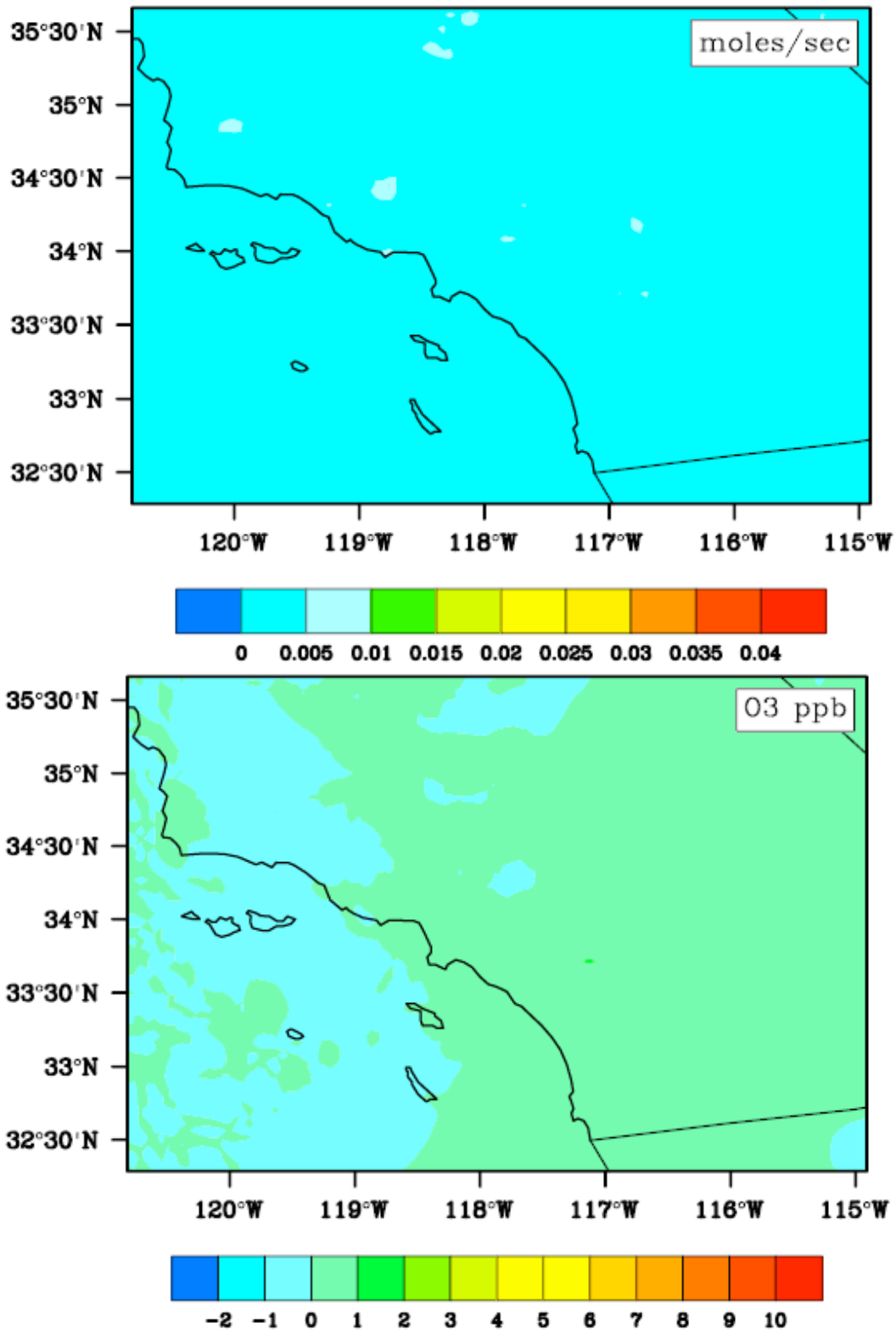

Figure 12. Difference between future and base case biogenic emissions and ozone concentrations on weekdays at 300 (second two panels) and 1500 (first two panels). Biogenic emissions in the scenario are based on temperature changes that have been adjusted by time of day. (Compare to Figure 4.)

Recommendations for further research include developing more detailed future emissions scenarios to describe in finer detail the likely range and spatial patterns of population growth and emission controls. Recent commitments to control greenhouse gas emissions in California may also affect criteria pollutant emissions, and this issue requires further study. While the present study considers factors that could affect the severity of a single high-ozone episode, further work is needed to quantify effects of climate change on the frequency of high-ozone days throughout the year. As noted above, the diurnal pattern of temperature change is important in assessing climate change effects on ozone air quality. More detailed information is needed on anticipated temperature changes as a function of time of day. Other investigators are considering effects such as changes in the number of stagnation events and length of the high-ozone season, and effects of climate change on other important air pollutants such as fine particulate matter. Fires may be an important aspect of ecosystem response to changing climate, and there could be large potential effects on air quality due to forest fires.

5.0 References

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